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Frank S. Gulczinski III[1]   John H. Schilling[2]

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

[1]Air Force Research Laboratory (AFMC)
AFRL/PRSS
1 Ara Road
Edwards AFB, CA 93524-7013

[2]W.E. Research
4360 San Juan Ct.
Rosamond, CA 93560

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Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

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Comparison of Orbit Transfer Vehicle Concepts Utilizing Mid-Term Power and Propulsion Options

Frank S. Gulczinski III
AFRL Propulsion Directorate (AFRL/PRSS)
1 Ara Road
Edwards AFB, CA 93524-7013
frank.gulczinski@edwards.af.mil

John H. Schilling
W.E. Research
4360 San Juan Ct.
Rosamond, CA 93560
schillin@spock.usc.edu

ABSTRACT

The recent announcement of a national nuclear space flight initiative[1] has rekindled interest in nuclear propulsion options within the spacecraft propulsion community. Therefore, the Air Force Research Laboratory Propulsion Directorate (AFRL/PRSS) has decided to reexamine the value of utilizing nuclear propulsion for orbit transit and the repositioning of future Air Force space assets. A trade study was conducted with the assumption that technologies had matured to the 2010 level. A comparison was made between advanced chemical, solar thermal, solar electric, and nuclear electric for expendable, integral, and reusable mission concepts, with a particular interest in options that resulted in trip times of 60 to 100 days. Results show that for expendable stages both solar thermal and, to a greater degree, solar electric propulsion systems can provide a significant increase in payload delivered from LEO to GEO within the required trip times. The solar electric concepts utilize clustered Hall thrusters, thin film photovoltaic solar arrays for power generation, and advanced power processing topologies for power conversion. Solar electric systems were also highly advantageous for integral systems. For reusable vehicles, where payload and fuel are supplied to a reusable propulsion tug module, similar results were calculated based on trip time. However, with a reusable stage, other considerations related to component degradation in the space environment must be considered. This consideration results in a rapid degradation of the thin film arrays used for solar electric stages due to Van Allen belt radiation, whereas the reactors utilized for the nuclear electric options are hardened to prevent radiation damage to payload and thus are protected from the natural space environment. Nuclear reactors also have a large initial dry mass penalty that limits their applicability for transporting small payloads. Thus, for a reusable orbit transfer vehicle, a nuclear electric tug becomes an attractive option for repositioning and transiting very large future Air Force space assets.

INTRODUCTION

This work presents the results of trade studies by AFRL/PRSS to investigate advanced propulsion options for orbit transfer vehicles (OTVs). The development of an OTV is an Air Force Space Command near-term priority[2] and advanced propulsion can significantly augment the payload delivery capabilities of an OTV. In this study, a baseline LEO to GEO mission was examined.

This study looks at propulsion systems, advanced to the projected 2010 levels, coupled with advanced power generation systems: thin film photovoltaic solar arrays[3] or nuclear reactors. The inclusion of nuclear reactors results from the new national nuclear space flight initiative.[1] It is unclear whether or not a system with a nuclear reactor will ever be politically acceptable in low earth orbit, regardless, they are included here based on technical merit. The classes of propulsion system considered were solar electric, nuclear electric, solar thermal, and chemical.

Three types of OTV architectures were considered: expendable, integral, and reusable. For expendable systems, the payload and OTV are launched together on a single launch vehicle. Once the transfer from LEO to GEO is completed, the OTV is disposed into a supra-GEO orbit and not used for spacecraft stationkeeping or power generation due to its large inertia, the (presumed) inappropriateness of its power level, and solar array degradation during the passage through the Van Allen belts. Integral systems retain the OTV array and propulsion system for

spacecraft power generation and stationkeeping. The calculations in this paper do not account for the additional stationkeeping propellant that will be required due to the inertia of the oversized solar arrays, but this impact is expected to be minimal. For Reusable OTVs, a modular approach was employed. The OTV, consisting of propulsion system, power generation system, and major bus components is launched first. It was decided that the OTV would be permitted up to two launches, followed by autonomous on-orbit assembly. The payload and propellant required to transfer the vehicle from LEO to GEO and back will then be launched and will dock with the OTV. The goal was to compare systems capable of performing 25 transfers, carrying spare thrusters and a sufficiently large power system to account for degradation. It was found, however, that solar electric systems were not capable of meeting this goal, as will be discussed below. For the expendable and reusable systems, there is minimal action between the payload and OTV – no sharing of power and propellant except for payload housekeeping (should it be required).

In order to keep transit times on par with satellite check-out periods, they were constrained to less than 120 days, with a preference for 60 to 100 day trips. The initial payload mass will be determined by the launch vehicle – four different launchers were considered: Delta II (7920), Atlas IIAS, Delta IV Medium+ (5,4), and Delta IV Heavy. The initial orbit in LEO was 400 km, 28° for all non-nuclear systems, with the nuclear systems constrained to a minimum orbit of 800 km, 28° to address safety concerns. The transfer assumed a constant thrust, spiral transfer for low thrust systems and a classical Hohmann transfer for high thrust (chemical systems). For mid-level thrust systems (solar thermal and high power electric propulsion), perigee arc burns were used with durations determined by the analysis optimization code.

The propulsion systems considered in this study consisted of thrusters, power processing units (where applicable), and propellant management assemblies. The propulsion system configurations that were found to trade well and remained in the final results were:

Expendable

- Storable Chemical
- Cryogenic Chemical
- Solar Thermal
- Solar Electric Hall Effect Thruster
- Nuclear Electric Hall Effect Thruster

Integral

- Solar Electric Hall Effect Thruster

Reusable

- Solar thermal
- Nuclear Electric Hall Effect Thruster

For the integral systems, the non-electric propulsion concepts dropped out since they would require an additional power system to be carried for on-orbit operations. The nuclear electric Hall thruster was found to trade poorly for expendable cases and was not included for the similar integral cases. For reusable systems, chemical propulsion was not competitive due to their low specific impulse which exacerbated the need to carry propellant for the return trip. Solar electric systems were not competitive due to solar array issues. Though tests have shown that thin film arrays are far more resistant to electron damage than crystalline arrays, resulting in a far longer lifetime in LEO or GEO, they have not demonstrated the same resistance to the protons they would encounter while transiting from LEO to GEO through the Van Allen belts. Based on current, *but preliminary*, data[4] it appears that thin film arrays have sufficient proton resistance to survive approximately three 60 day LEO – GEO transfers. Since a reusable OTV can deliver 10 – 15% more payload, it will require approximately 6 to 10 transfers to overcome the launch mass penalty incurred by launching the OTV separately. Thus, based on this preliminary thin film array degradation data, it appears that solar electric reusable orbit transfer vehicles are still not a practical option. The AFRL Space Vehicles Directorate is currently performing experiments to better quantify the proton resistance of thin film arrays and results are expected by mid-2003, at which time the AFRL Propulsion Directorate will reassess their applicability to reusable OTV propulsion systems.

The thin film arrays used in this study assumed a specific power of 200 W/kg. The solar thermal concentrators had a thermal specific power of 1500 $W_{thermal}$/kg. However, above 100 kW, the mass of solar electric and solar thermal systems was scaled as power to the 3/2 power to account for structural and wiring mass beginning to dominate the system. The nuclear reactors examined in this study were scaled based on a curve fit of past reactor designs (including radiator and shielding). Those designs that progressed beyond the conceptual stage to hardware testing were weighted more heavily.

The strategy of the analysis was to set the initial mass and trip time as independent variables, and determine all other parameters from the analysis. The initial mass in LEO was set, which determined the amount of propellant needed to transfer the vehicle to GEO (dependant on the specific impulse of the propulsion system under consideration). It is then possible to determine the system power and mass delivered for a given trip time based on the thrust of the propulsion system under consideration. The results are presented in the following section.

OTV PAYLOAD DELIVERED AND MASS BREAKDOWNS

In this section, the results of the analysis are presented. For each launch vehicle, a chart showing payload mass delivered versus trip time will be given for the eight different configurations that were found to be competitive. Expendable, integral, and reusable cases will be presented on the same chart. Also presented will be a chart showing the mass breakdown by subsystem for a 100 day transfer time. Masses for subsystems were determined based on established scaling relationships.[5] On these mass breakdown charts will be the power levels dictated for electric propulsion systems for the 100 day transfer and the size of the solar thermal concentrators used.

Delta II (7920)

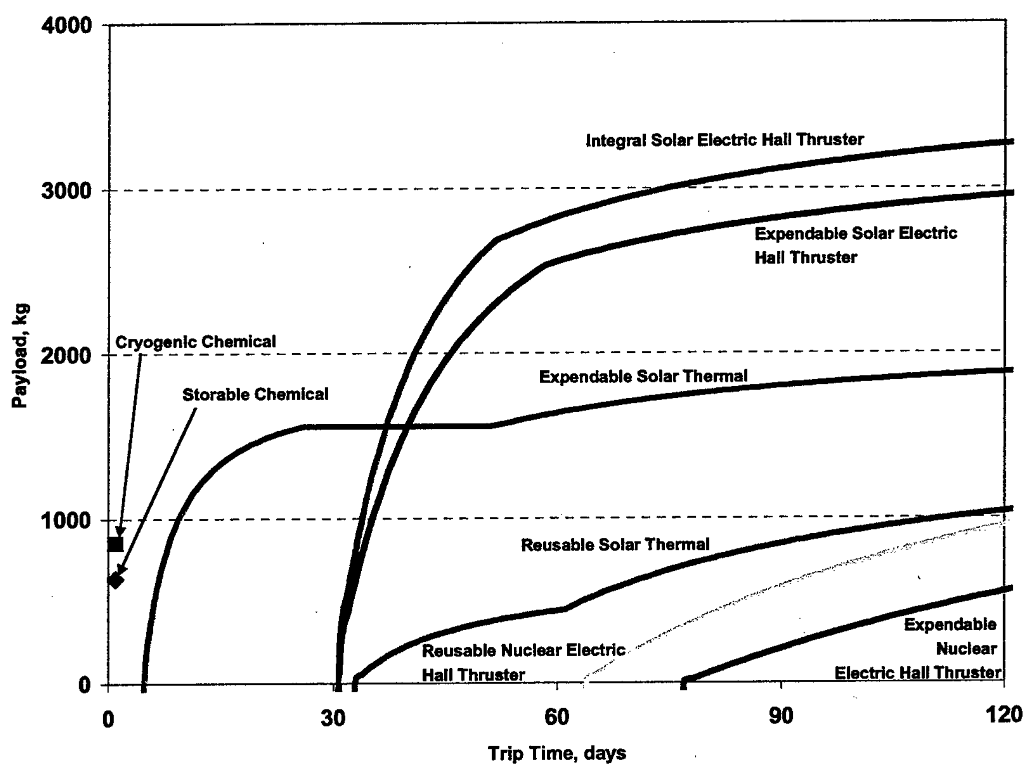

Figure 1: Payload Mass Delivered for Delta II (7920) versus Trip Time

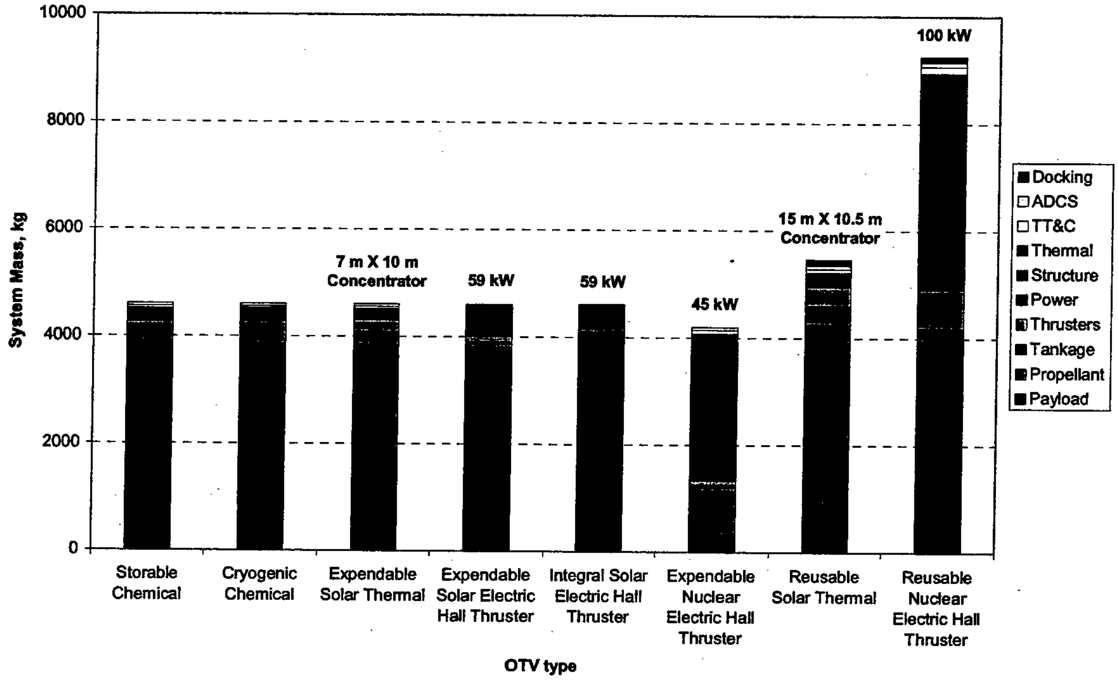

Figure 2: Mass Breakdowns for Delta II (7920) with 100 Day Trip Time

In Figure 1 we see, as expected, that chemical systems are required for rapid transits, with cryogenic chemical systems providing the most payload. If the trip time is allowed to grow to a week or more, solar thermal becomes an attractive option, but its payload delivery capability plateaus, and beyond ~30 days, the integral and expendable solar electric Hall thrusters are the optimal choice. The integral system delivers additional payload by allowing for the offloading of stationkeeping thrusters and on-orbit arrays. The reusable concepts do not compete well for this payload level, with solar thermal hampered by propellant mass for the return trip and nuclear electric by the reactor's dry mass. The 59 kW power level for the Hall thruster systems shown in Figure 2 is large, but not unobtainable within the next 10 years. The slight knee in the integral solar electric curve in Figure 1 at around 52 days and in the expendable solar electric curve at 58 days represents the 100 kW point where mass begins to increase with the power raised to the 3/2 power.

ATLAS IIAS

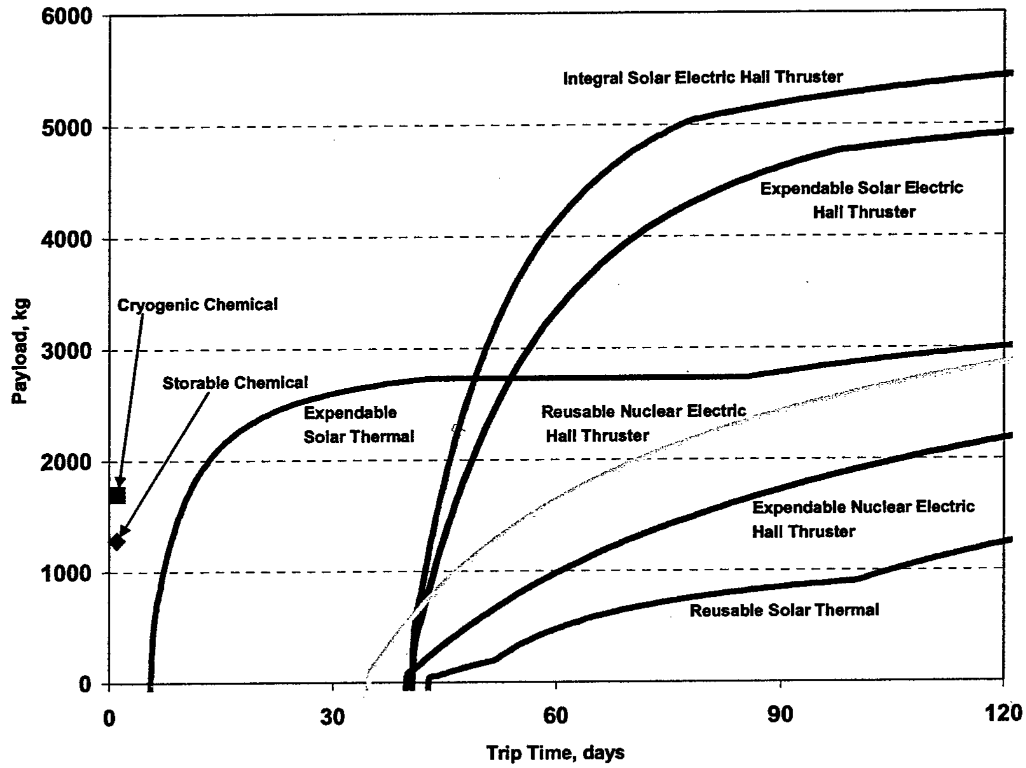

Figure 3: Payload Mass Delivered for Atlas IIAS versus Trip Time

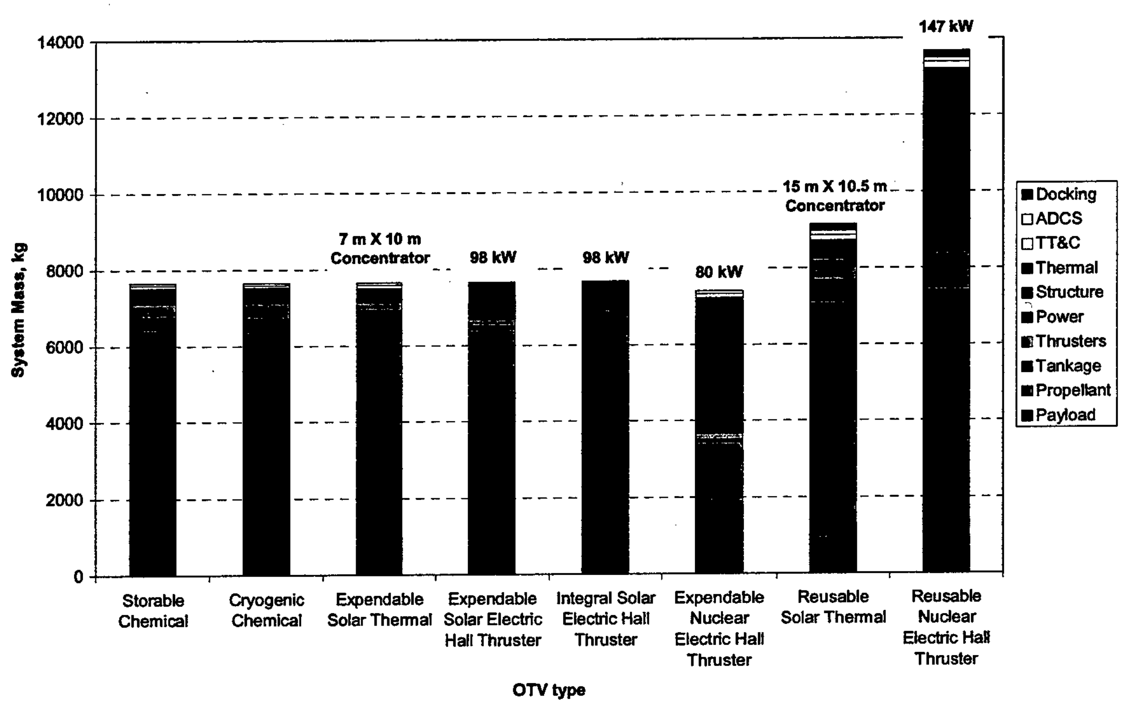

Figure 4: Mass Breakdowns for Atlas IIAS with 100 Day Trip Time

Figure 3 shows that the results for the Atlas IIAS are fairly similar to the Delta II, with the transition to solar electric optimization occurring around 40 days. A key point to note, however, is that the nuclear systems are improving relative to the other systems, with reusable nuclear electric outperforming reusable solar thermal. In Figure 4, we see that the power levels are quickly escalating to nearly 100 kW, where structure and wiring masses begin to dominate the array subsystem.

Delta IV Medium+ (5,4)

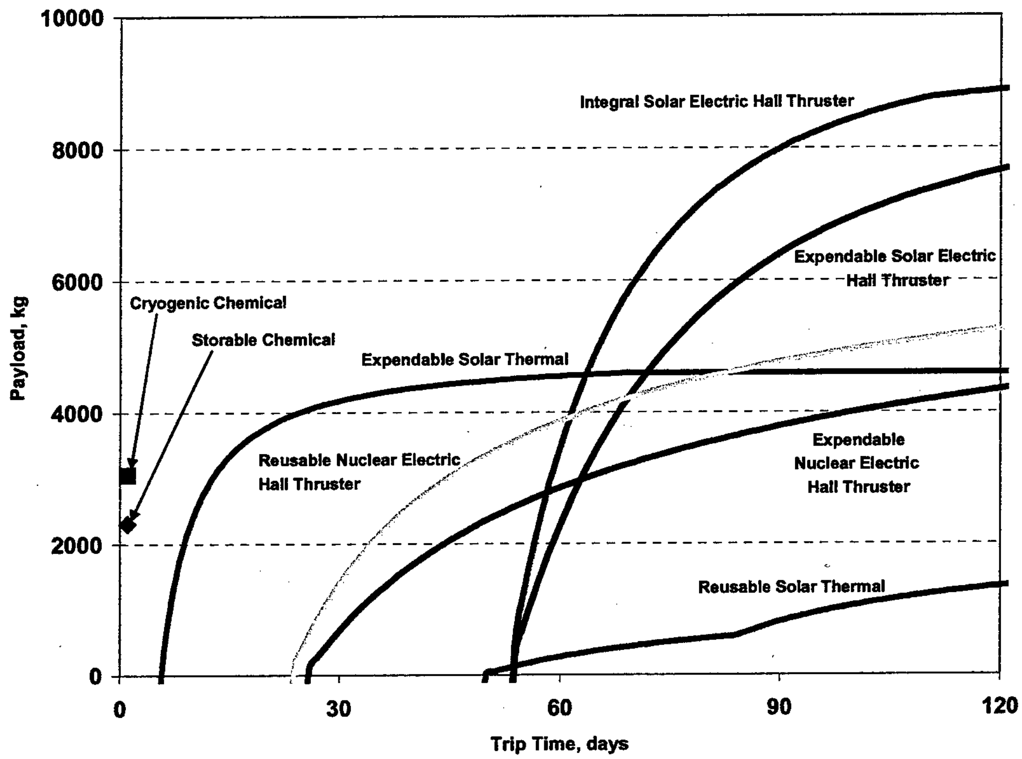

Figure 5: Payload Mass Delivered for Delta IV Medium+ (5,4) versus Trip Time

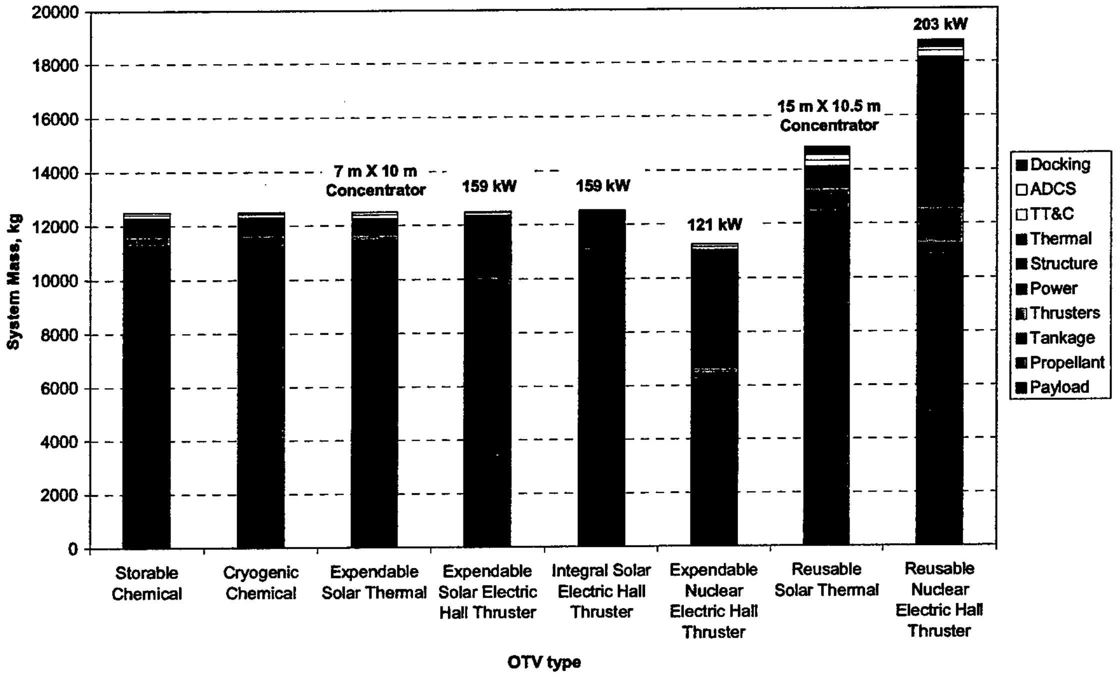

Figure 6: Mass Breakdowns for Delta IV Medium+ (5,4) with 100 Day Trip Time

Again, the same trends are seen in Figures 5 and 6. The optimization crossover from solar thermal to solar electric occurs just after 60 days. The nuclear electric systems are becoming more competitive, with the reusable configuration passing expendable solar thermal at just under 90 days.

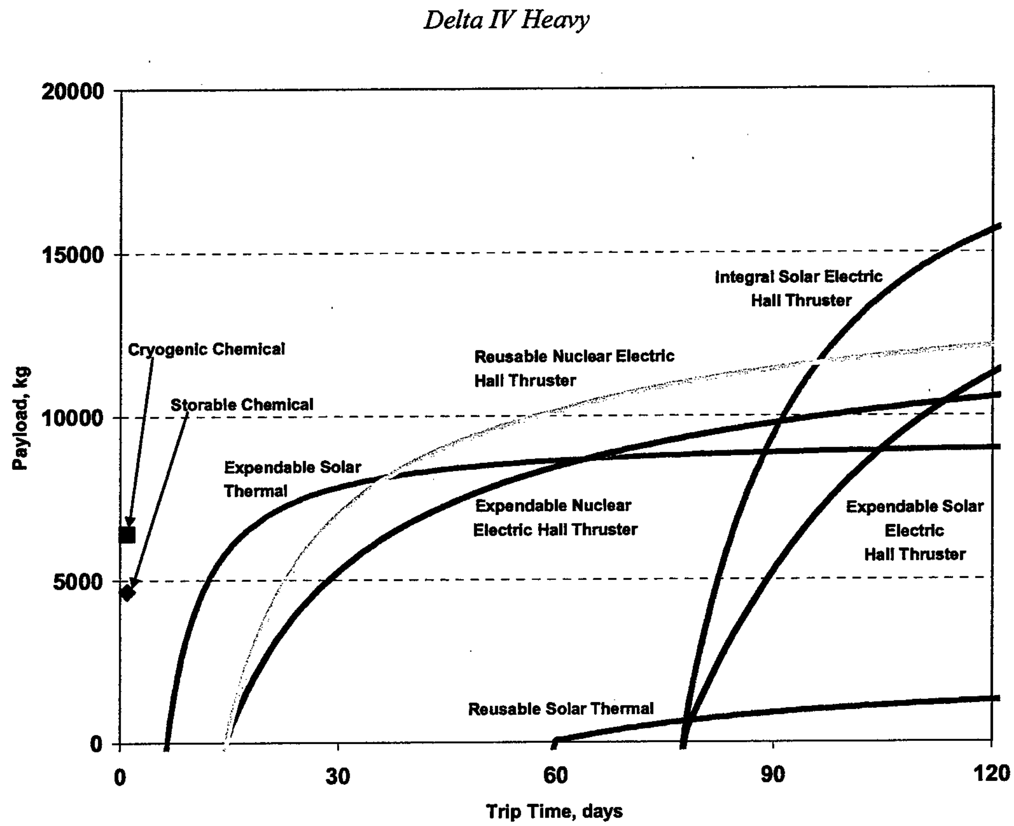

Figure 7: Payload Mass Delivered for Delta IV Heavy versus Trip Time

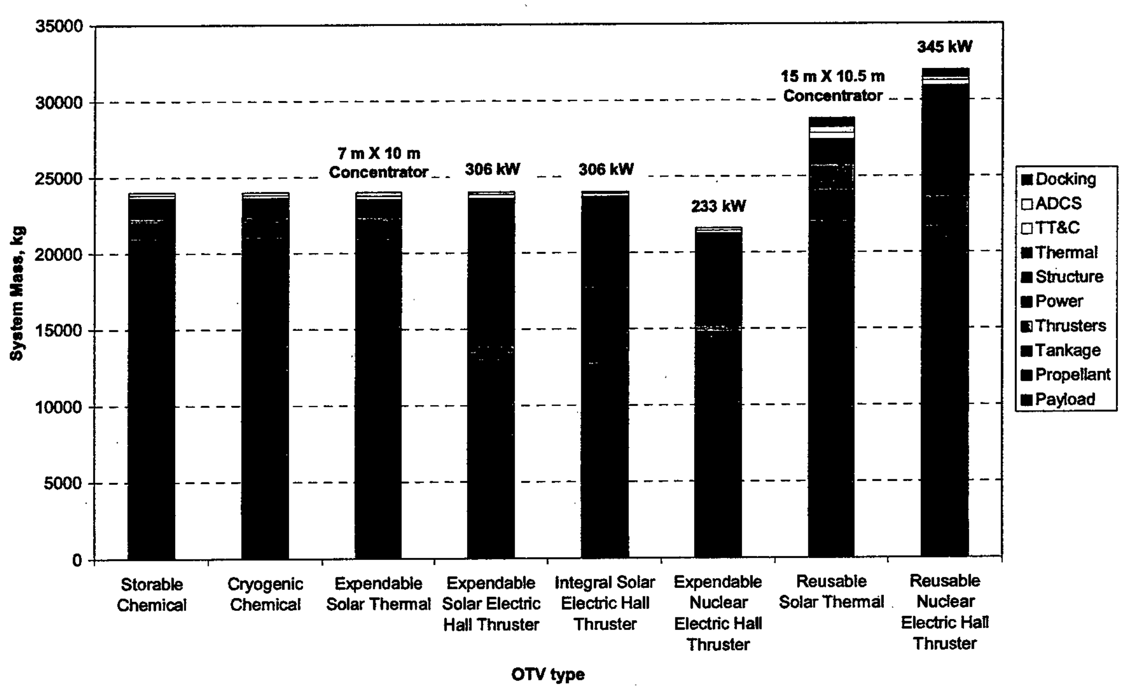

Figure 8: Mass Breakdowns for Delta IV Heavy with 100 Day Trip Time

When we reach the large Delta IV Heavy, we note a definite paradigm shift. As shown in Figure 7, nuclear electric systems become the optimal choice for transferring large payloads in time frames of under 95 days. These large DoD space assets are highly likely to have large power requirements, thus providing synergy with the high power levels shown for the nuclear electric propulsion systems shown in Figure 8.

SUMMARY AND CONCLUSIONS

For launches on vehicles smaller than the Delta IV Heavy, the trends were the same. Chemical systems are the only option for transfers of less than a few days, and cryogenic chemical systems offer superior performance. Expendable solar thermal systems increase the payload delivered for trip times of a week until the point where the high specific impulse of solar electric Hall thrusters surpass them, which ranges from 30 to 60 days, increasing with increased initial mass. When we reach the Delta IV Heavy, however, nuclear systems overcome their reactor dry mass penalties and become the optimal solution for non-rapid positioning of very large, very high power Air Force assets.

The primary technical challenges in developing the electric propulsion systems for these orbit transfer vehicles do not lie with the thrusters themselves. Programs underway at Air Force and NASA to push Hall thruster technologies to power levels of 50 kW and above have met with a great deal of initial success. Where the technology challenges lie are in the areas of power generation and power processing, including the development of large scale efficient thin film photovoltaic solar arrays, developing space nuclear reactors, and the development of lightweight power processing units. Solar thermal propulsion systems appear to be highly promising, but lack the validation of an in-space demonstration.

The AFRL Propulsion Directorate is continuing to work toward the goal of developing propulsion for an Air Force OTV. Trade studies such as this one support technology direction activities. A strong modeling and simulation program is examining the issues related to scaling thrusters and systems to very high powers. An experimental program has begun to look at issues related to operating Hall thrusters in clustered configurations[6] and is being coordinated with NASA's work to develop a monolithic 50 kW Hall thruster[7] to achieve the end goal of demonstrating a propulsion system capable of delivering the 100's of kW of propulsive power needed for an orbit transfer vehicle to support the needs of future Air Force warfighers.

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